

Convective dust clouds in a complex plasma

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The plasma is generated in a low frequency glow discharge within an elongated glass tube oriented vertically. The dust particles added to the plasma are confined above the heater and form counter-rotating clouds close to the tube centre. The shape of the clouds and the velocity field of the conveying dust particles are determined. The forces acting on the particles are calculated. It is shown that convection of the dust is affected by the convective gas motion which is triggered, in turn, by thermal creep of the gas along the inhomogeneously heated walls of the tube.

Convective motion of micro particles in complex (dusty) plasmas is a phenomenon that is often observed in very different experimental conditions. In particular, vortices in complex plasmas can be produced both in ground-based laboratories and under microgravity conditions, in dc and rf discharges of fairly different configuration, upon inhomogeneous heating and in rather isothermal environment [1].

There are many publications, both theoretical and experimental, in which the origin of the vortex motion in complex plasmas has been investigated [2, 3, 4, 5, 6, 7, 8, 9]. Basically, there are two mechanisms that can produce vortices: This is either the presence of non-potential force(s) exerted on charged micro particles in the discharge (due to inhomogeneous charges [7] or because of ion drag [9]) or the convective motion of the background neutral gas or dust particles themselves [10]. This clearly indicates that the nature of such vortices – despite of quite similar appearance – might be very different as well.

In this paper we report on a recent experiment performed in a low frequency glow discharge under gravity. The PK-4 setup [11, 12] was used, which represents a typical configuration of a dc discharge employed to study complex plasmas. We investigate convective motion of micro particles in the presence of an external controllable heating and unambiguously show that under such conditions vortices in complex plasmas occur due to the neutral gas convection. Clouds of micro particles in this case resemble convective clouds in the atmosphere produced from warm air pockets rising upwards and composed of water droplets, ice crystals, ice pellets, etc.

The experiments were conducted in a complex plasma produced by a low frequency discharge (LFD) in Neon gas of the PK-4 facility [11, 12]. The plasma chamber consists of an elongated glass tube as shown in figure 1. To remove all rest gases which might disturb the experiments the chamber was evacuated for several hours to reach a base pressure below $10^{-3}Pa$. Neon gas with constant pressure between $30Pa$ and $100Pa$ were used during the experiments.

A gas discharge was maintained between the electrodes by a regulated discharge current of $1mA$. The discharge voltage polarity was changed with a frequency of $1kHz$ (50% duty cycle). This frequency is more than an or-

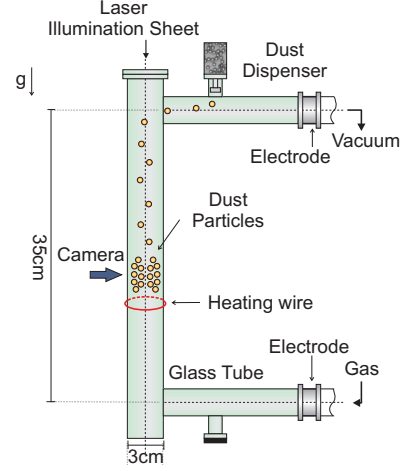


FIG. 1: Experimental setup.

der of magnitude higher than the dust-plasma (response) frequency [1], so that the effective longitudinal force on micro particles (electric plus ion drag) vanishes.

In course of the experiments micro particles (spherical Melamine-Formaldehyde particles with a mass density of $1.51g/cm^3$) of two different radii $r_p = 1.64\mu m$ or $3.05\mu m$ were injected by a dispenser from above into the plasma and confined inside of the vertical glass tube. The micro particles were illuminated along the tube axis by a laser sheet (wave length $686nm$, power $20mW$, thickness $100\mu m \pm 30\mu m$, width $15mm$) and the images were recorded by a PCO 1600 camera.

A metal wire (alloy of 70% Ni, 11% Fe, and 14% Cu and $0.5mm$ in diameter) was put around the lower part of the tube to produce a temperature gradient. A dc current between $0.5A$ and $1.8A$ was applied to this wire using a $10V$ power supply. For avoiding unwanted electromagnetic effects on the plasma only one loop of the wire was attached. The wire was insulated against direct contact to the tube walls. The resulting temperature distribution was simultaneously measured at eight points on the glass tube at and above the heating wire to extract the temperature gradient over a range of $8cm$.

Due to the gas temperature gradient a thermophoretic force acts on the micro particles [13]. This was used to

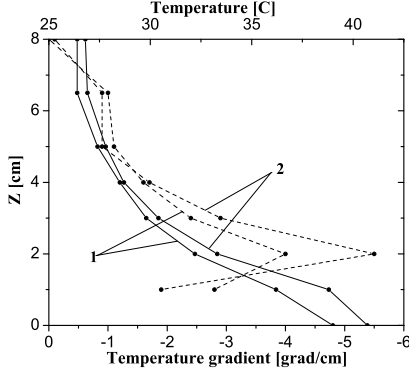


FIG. 2: Measured temperatures (solid lines) and calculated temperature gradients (dashed lines). 1: temperature and temperature gradient for $r_p = 1.64\mu\text{m}$ particles, 2: same for $r_p = 3.05\mu\text{m}$ particles.

levitate micro particles against gravity in complex plasma experiments [14]. The thermophoretic force acting on the micro particles is given by

$$\mathbf{F}_{th} = -\gamma_{th}\nabla T_n, \quad (1)$$

where $\gamma_{th}[\text{N} \cdot \text{cm}/\text{K}] \simeq 2.17 \times 10^{-6} (r_p[\mu\text{m}])^2$ [14]. The thermophoretic force required to levitate particles is $F_{th} = m_p g \simeq 2.74 \times 10^{-13} \text{N}$ for the smaller ones and $\simeq 1.76 \times 10^{-12} \text{N}$ for the larger ones (m_p is the particle mass). Therefore according to (1) temperature gradients of $|dT/dz| \simeq 4.65 \text{K}/\text{cm}$ for the smaller particles and $\simeq 8.64 \text{K}/\text{cm}$ for the larger ones are required to compensate gravity.

The measured temperatures along the tube and the temperature gradients are shown in figure 2, where $z = 0$ is the position of the heating wire. It turns out that the measured maximum values of the temperature gradients are smaller than those necessary for thermophoretic levitation. Nevertheless we observe that the particle cloud is confined in the area above the heating wire. Figure 3 shows vertical cross sections through the center of the clouds obtained for different pressures. As we pointed out above, plasma forces cannot be responsible for this effect: because of the fast polarity switching, neither a longitudinal electric force nor an ion drag force [15] could support the levitation. In addition, an intense convective motion of the particles is observed within the levitated clouds.

The micro particles are frictionally coupled to the neutral gas. Therefore, it is natural to assume that gas convection is induced by the local tube heating and that the micro particles are dragged by the gas motion. Favorably directed, the gas flow could help to levitate the particles in addition to thermophoresis and also could result in global dust rotation. Note that \mathbf{F}_{th} alone cannot cause the convection, because it is a potential force,

$$\nabla \times \mathbf{F}_{th} \equiv 0.$$

The neutral drag force acting on a spherical particle within a gas flow is given by [16]

$$\mathbf{F}_n = \gamma_n(\mathbf{v}_f - \mathbf{v}_p), \quad (2)$$

where the Epstein friction coefficient reads $\gamma_n[\text{N} \cdot \text{s}/\text{cm}] \simeq 2.7 \times 10^{-16} (r_p[\mu\text{m}])^2 p[\text{Pa}]$ for Neon at room temperature, $T_n = 300 \text{K}$.

The radial electric field of discharge exerts an additional force F_r [17] which confines the particle cloud in radial direction. We observed that the micro particles after switching off the discharge expand across the tube, exploiting practically the entire convective field. Particles keep rotating one or two cycles before eventually falling down.

As an example, let us extract the velocity field \mathbf{v}_f of the convective gas flow and the radial electric force \mathbf{F}_r for the experiment with $3.05\mu\text{m}$ particles at a pressure of 50Pa .

Particle motion is recorded at a frame rate of 500fps in course of the experiment comprising two separate cases: with and without plasma. The particles are detected in each frame and then based on the position of each particle in a few consecutive frames their velocities and accelerations are extracted. Based on this data, the particle velocity profiles are reconstructed in the entire convective dust cloud. Particle velocities and accelerations are derived by fitting cubic splines to the complete particle trajectories.

The trajectories of individual particles are determined by the balance of forces:

$$m_p \ddot{\mathbf{r}} = \mathbf{F}_{th} + \mathbf{F}_n + \mathbf{F}_r + m_p \mathbf{g}. \quad (3)$$

To separate the remaining unknown forces – the radial electric force and the neutral drag force – appearing in (3), we analyze first the data when no plasma was in the tube, and, hence, no radial electric force ($F_r = 0$) acts on the particles. This allows us to get the velocity field of the conveying gas molecules. Next with this information and assuming that switching on and off the plasma does not alter the gas convection, we calculate the radial electric force of the plasma in the region where particle trajectories recorded with and without plasma overlap (cf. figure 4). Switching off the plasma is a very fast process compared to the time particles spend conveying in the tube. Particles trajectories for both cases are shown in figure 4. In figure 4(a) the particle cloud in the presence of the plasma is a bit higher and further away from the tube wall. After switching off the plasma 4(b) particles come closer to the wall and the cloud expands further down. The area of particle clouds and the direction of rotation for these two cases are represented in (c) with the overlapping region marked. For the overlapping region any differences in the particle motion between the cases with and without plasma must be due to electrical forces as

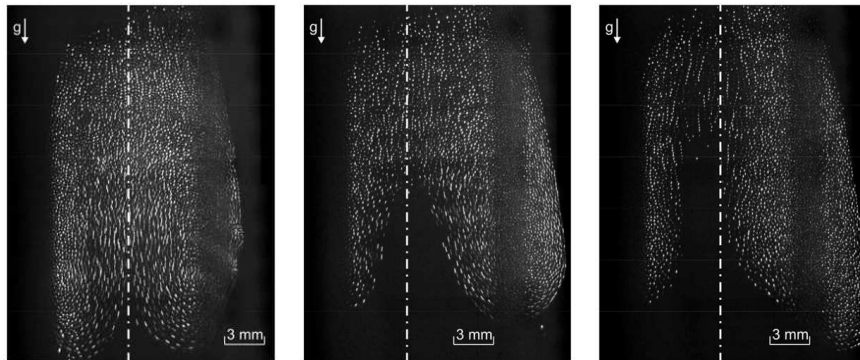


FIG. 3: Dust clouds of $r_p = 1.64\mu\text{m}$ particles at 30, 50, and 100Pa (from left to right). The dash-dotted lines indicate the center of the tube. The field of view is $21 \times 26\text{ mm}$.

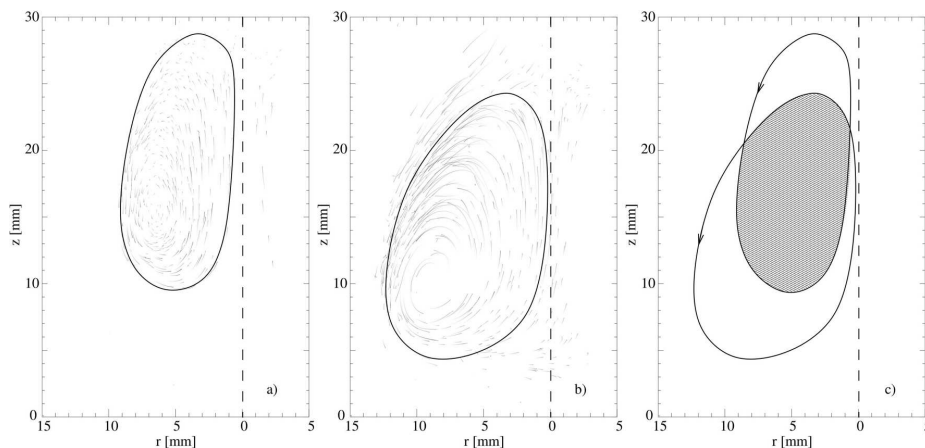


FIG. 4: Convective dust clouds of $r_p = 3.05\mu\text{m}$ particles at a pressure 50Pa for two different cases, (a) with switching on of the plasma and (b) with switching off the plasma. (c) The superimposed cloud positions for these two cases. The arrows indicate the directions of particle rotations. The region of overlapping trajectories is shaded. The dashed lines indicate the center of the tube.

the distribution of temperature and free gas convection are not influenced by the discharge.

The neutral drag force on the particles depends on the relative velocities of the particles and gas. This is the reason why the particles do not follow the gas flow trajectories but rotate eccentrically from the center of gas convection in the area of upward gas draft. Figure 5 presents the velocity field of the free gas convection as calculated for the case without plasma. The particle trajectories are overplotted. The distribution of flow velocities has a clear rotational tendency.

The radial force on the particles when plasma is on (cf. figure 6) can now be fitted using the gas flow velocities in the overlapping region. The radial force is zero at the tube axis and rapidly increases towards the tube walls.

The results obtained above clearly demonstrate the presence of gas convection. This is not free convection,

though, merely because the onset of free convection is too high in terms of the critical Reyleigh number (see, for instance [10]) to cause gas flow under the conditions of our experiments. It is well known, however, that if one puts a non-uniformly heated body in a rarefied gas, the gas starts moving along the body *in the direction* of the temperature gradient [18, 19, 20]. This phenomenon is referred to as *thermal gas creep* (or *thermal gas slip*). It was predicted theoretically by Maxwell [21] and verified experimentally by Reynolds [22] and is governed by the relation

$$V_{TC} = K_{TC}\nu\nabla_{\parallel}\ln T_W, \quad (4)$$

where V_{TC} is the velocity of creep at the body surface, ν is the kinematic viscosity of the gas, T_W is the temperature of the heated body, i.e. the glass walls in our case, and \parallel indicates the component of the gradi-

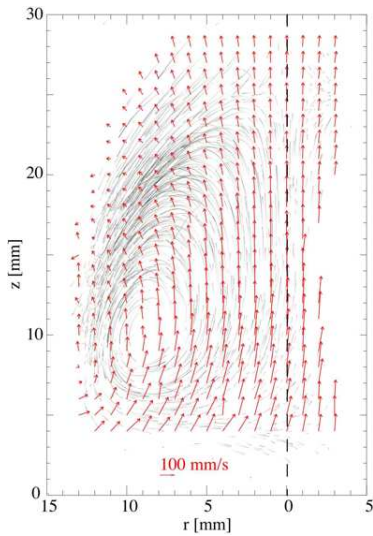


FIG. 5: Averaged gas flow velocity field (vectors) superimposed with particles trajectories. The dashed line correspond to the center of the tube.

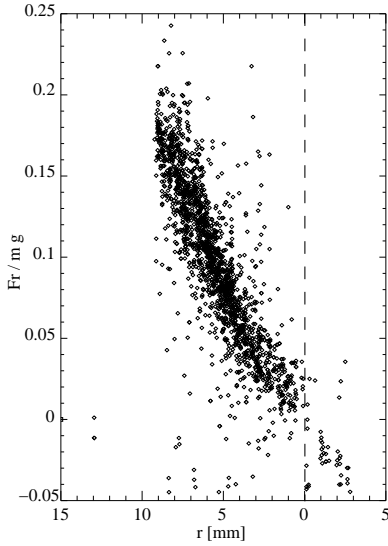


FIG. 6: Reconstructed radial force for the overlapping region. The dashed line indicate the center of the tube.

ent along the surface. For a long tube, the radial distribution of the (longitudinal) velocities is well known, $v_z = V_{TC}(2r^2/R^2 - 1)$ [20]. In our geometry the vertical temperature gradient is negative $dT_W/dz < 0$ (see figure 2). Hence, the gas should flow downwards along the tube walls with $v_z(R) = V_{TC}$ and upwards near the tube axis with $v_z(0) = -V_{TC}$, which is in agreement with our observations (see figure 5). For the quantitative comparison with the experiment, we rewrite Eq. (4)

in the following form: $K_{TC} = |V_{TC}/\nu \nabla_z \ln T_W|$. Based on the experimental data shown in figures 2 and 5 we get $K_{TC} \simeq 1$, which is in agreement with theoretical expectations. (The theoretically possible range of values of K_{TC} amounts to 0.7–1.2 [19]). Note also that the magnitude of the convection velocity decreased monotonically with pressure, which is also in line with the theoretical estimates: combining Eqs. (3) and (4), we obtain that the velocity should scale as $\propto p^{-1}$.

To conclude, we observed levitation of a particle cloud in a vertical glass tube, above a heated wire. In addition, the particles exhibited a global vortex flow. We showed that the particle vortices were induced by the convection of neutral gas analogously to convective clouds in the atmosphere. In turn, the gas convection was triggered by the thermal creep along the inhomogeneously heated tube surface.

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- [1] V.E. Fortov *et al.*, Phys. Rep. **421**, 1 (2005).
 - [2] O.S. Vaulina *et al.*, JETP **91**, 1147 (2000).
 - [3] P.K. Shukla, Phys. Lett. A **268**, 100 (2000).
 - [4] V.N. Tsytovich *et al.*, Phys. Plasmas **13**, 032306 (2006).
 - [5] S.N. Antipov *et al.*, Proc. of 33rd EPS Conference on Plasma Phys. **30I**, D-5.027 (2006).
 - [6] M. Rubin-Zuzic *et al.*, New. J. Phys. **9**, 39 (2007).
 - [7] V. Fortov *et al.*, JETP Lett. **96**, 704 (2003).
 - [8] O. Vaulina *et al.*, NJP **5**, 82 (2003).
 - [9] G. Morfill *et al.*, Phys. Rev. Lett. **83**, 1598 (1999).
 - [10] A.V. Ivlev *et al.*, Phys. Rev. Lett. **99**, 135004 (2007).
 - [11] V. Fortov *et al.*, Pl. Phys. Contr. Fusion **47**, B537 (2005).
 - [12] S. A. Khrapak *et al.*, Phys. Rev. E **72**, 016406 (2005).
 - [13] J. Tyndall, Proc. R. Inst. G.B., **6**, 3 (1870); W. Cawood, Trans. Faraday Soc., **32**, 1068 (1936); L. Waldmann, Z. Naturforsch. **14a**, 259 (1959).
 - [14] H. Rothermel *et al.*, Phys. Rev. Lett. **89**, 175001 (2002).
 - [15] A.V. Ivlev *et al.*, Pl. Phys. Contr. Fusion **46**, B267 (2004).
 - [16] P. Epstein, Phys. Rev. **23**, 710 (1924).
 - [17] Y.P. Raizer, *Gas Discharge Dynamics*, (Springer Verlag, Berlin, 1991).
 - [18] M.N. Kogan, *Rarefied gas dynamics*, (Plenum Press, New York, 1969).
 - [19] S. P. Bakanov, Usp. Fiz. Nauk **162**, 133 (1992).
 - [20] E. M. Lifshitz and L. P. Pitaevskii, *Kinetic theory of gases* (Pergamon Press, Oxford, 1981).
 - [21] J.C. Maxwell, Philos. Trans. R. Soc. London Ser. **B170**, 231 (1879).
 - [22] O. Reynolds, ibid. **170**, 727 (1880).